

MULTI-TeV MUON COLLIDER PHYSICS

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The most powerful way of discovering new particle physics is to design and build colliders with the highest energies possible. Muon colliders offer a promising avenue that might greatly extend the energy frontier of collider physics. One can contemplate circular colliders with center-of-mass energies in the multi-TeV range. There is no way to know at the present time what kind of physics will appear at these energy scales, but presumably data from the Large Hadron Collider and possible future lepton colliders will find physics beyond the Standard Model and motivate the direction that particle physics should take in the coming decades. In this article some physics issues that might be relevant at a multi-TeV muon collider are discussed.

Introduction

The large mass of the muon compared to that of the electron results in a large suppression of bremsstrahlung radiation. Consequently it is possible to consider building circular colliders with energies in the multi-TeV regime^{1,2}. Muon colliders have been proposed as Higgs factories and more recently as neutrino factories, but the long-term goal of muon colliders should be to extend the energy frontier. It is hard to know what kind of physics might present itself in the multi-TeV mass range. After all, physicists have been arguing for a long time about the physics that will manifest itself at the lower subprocess energies at the Large Hadron Collider (LHC). The LHC, linear electron-positron colliders, and perhaps a first muon collider should give us some clue as to what to expect at the following generation of machines. It is easy to imagine scenarios where a new collider might be necessary, but it is impossible to convincingly motivate a specific model or a required energy at this time. We can only speculate as to what physics might appear at the LHC or future linear colliders.

In light of our ignorance of the new physics that might present itself between a few hundred GeV and 10 TeV, one can appeal to quite general arguments such as those based on unitarity to anticipate what kind of physics might lie at very high energies. Certainly data from the LHC and an e^+e^- linear collider will point to more specific possibilities. Since the trend toward ever longer timelines in accelerator and physics planning is continuing, physicists are thinking now about what kind of physics may present itself in the post-LHC era. In this note, I discuss just a few of the possibilities.

Luminosity requirements

The difficulties that are present at very high energies for e^+e^- colliders are associated with the small mass of the electron: there is large bremsstrahlung, beam-beam interactions, etc. A muon collider largely eliminates these problems, but muon colliders have their own constraints: the muons decay so that acceleration has to take place very rapidly, and muons do not occur naturally but have to be produced through pion decay. These factors impact the available luminosity of the collider, which after the center-of-mass energy is the second most important parameter after the energy of the collider that determines the physics potential of the machine.

While we do not know what physics we will be studying at future multi-TeV colliders, we know on general grounds that cross sections decrease like the energy squared, so higher energies require higher luminosities. The figure of merit for physics searches at a muon collider is the QED cross section $\mu^+\mu^- \rightarrow e^+e^-$, which has the value

$$\sigma_{QED} = \frac{100 \text{ fb}}{s \text{ (TeV}^2\text{)}} \quad (1)$$

To arrive at a simple estimate of the integrated luminosity needed to study new physics, we following the original survey³ of the particle physics of muon colliders and require

$$\left(\int \mathcal{L} dt \right) \sigma_{QED} \gtrsim 1000 \text{ events} , \quad (2)$$

as a minimum number of events to have a reasonable physics program. Then the luminosity requirement for this number of events to be accumulated in one year's running is

$$\mathcal{L} \gtrsim 10^{33} \cdot s \text{ (cm)}^{-2} \text{ (sec)}^{-1}$$

For the colliders with the center-of-mass energies of 1 TeV, 10 TeV and 100 TeV, one obtains

- $\sqrt{s} \simeq 1 \text{ TeV}$, requiring

$$\int \mathcal{L} dt \gtrsim 1 \text{ (fb)}^{-1}, \quad \mathcal{L} \gtrsim 10^{33} \text{ (cm)}^{-2} \text{ (sec)}^{-1}$$

- $\sqrt{s} \simeq 10 \text{ TeV}$, requiring

$$\int \mathcal{L} dt \gtrsim 1 \text{ (fb)}^{-1}, \quad \mathcal{L} \gtrsim 10^{35} \text{ (cm)}^{-2} \text{ (sec)}^{-1}$$

- $\sqrt{s} \simeq 100 \text{ TeV}$, requiring

$$\int \mathcal{L} dt \gtrsim 1 \text{ (fb)}^{-1}, \quad \mathcal{L} \gtrsim 10^{37} \text{ (cm)}^{-2} \text{ (sec)}^{-1}$$

These benchmark luminosity targets are necessary to obtain reasonable statistical samples.

Electroweak symmetry breaking

A multi-TeV muon collider might be very useful for exploring the physics responsible for electroweak symmetry breaking if a Higgs boson is not found at the LHC. General arguments based on unitarity violation require that interactions of longitudinally polarized weak bosons (W_L, Z_L) become strong and can be probed by studying vector boson scattering as shown in the figure. Therefore, new physics must be present somewhere near the TeV energy scale.

It should not be forgotten that if strong scattering is indeed present in longitudinal gauge boson interactions at a few TeV, it will not be sufficient just to observe the presence of the nonperturbative effects. While one can study strong $W_L W_L$ scattering at the LHC and lepton colliders with at least a TeV center-of-mass energy, it might become necessary to go to higher energies to fully explore the multitude of resonances. Higher energies would be required to uncover the undoubtably rich physics in the electroweak symmetry

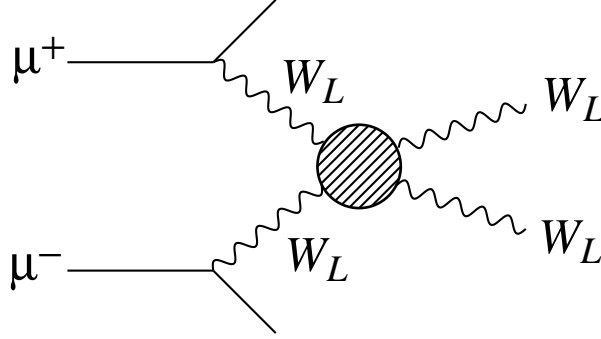


Figure 1. Strong scattering of electroweak bosons.

breaking sector. The spectrum of states must be observed to fully uncover the nature of the interactions. After all, there is more to the analogous phenomenology of QCD than $\pi\pi$ scattering. Indeed we are still studying the spectrum of QCD today.

Experimentally this task will prove to be quite difficult. The spectrum of states will decay into channels that are plagued by large Standard Model backgrounds. It will prove very challenging to unravel the physics, and we can expect this to be a multi-decade effort.

Fermion mass generation

The mechanism responsible for fermion masses and the mechanism breaking the electroweak symmetry are the same in the Standard Model. A Higgs scalar acquires a vacuum expectation value giving rise to massive gauge bosons and (through Yukawa couplings) masses for the fermions. However, it need not be the case that these mechanisms are the same, and technicolor models are the most prominent examples of theories where the fermion masses arise from a different sector from that responsible for the electroweak symmetry breaking. Hence one should keep an open mind about the origin of fermion masses.

Constraints from unitarity violation require that the mechanism that generates fermion mass be below some energy scale. The relevant bound for fermions scattering into longitudinally polarized vector boson V_L ,

$$f\bar{f} \rightarrow V_L V_L , \quad (3)$$

is the Appelquist-Chanowitz bound⁴ which states that unitarity is violated at the scale

$$\Lambda_f < \frac{8\pi v^2}{\sqrt{3N_c}m_f} , \quad (4)$$

where $v = (\sqrt{2}G_F)^{-1/2}$ is the electroweak vev and N_c is the number of colors of the fermion. In the Standard Model this unitarity violation is cured by the inclusion of the s -channel Higgs exchange diagram. The strongest bound comes for the heaviest fermion the top quark for which $\Lambda_t \approx 3$ TeV, indicating that some new physics must occur below this scale.

For a muon one gets $\Lambda_\mu \approx 8,000$ TeV. So if the physics responsible for the muon mass saturates this bound, it is beyond the reach even of a 10-100 TeV muon collider. But one does not reasonably expect that the bound is saturated, but rather that the fermion masses are all generated at a common scale with some masses suppressed by some approximate flavor symmetries. In light of the lower value of Λ_t , one might expect a 10 TeV collider to provide important insight into fermion mass generation if Nature is not so kind to provide a elementary scalar particle. In the typical case one expects the resonances to be broad. In some scenarios⁵, one can have strongly interacting Higgs sectors with narrow resonances for which the naturally small energy spread might be helpful.

One can also study the unitarity violation in the subprocess $V_L V_L \rightarrow t\bar{t}$, analogous to the case discussed in the previous section for electroweak symmetry breaking. This process could also be sensitive to new physics responsible for the fermion masses, and one would measure the cross sections for $\mu^+ \mu^- \rightarrow \nu \bar{\nu} t\bar{t}$ and $\mu^+ \mu^- \rightarrow \mu^+ \mu^- t\bar{t}$, and in scenarios where the unitarity is saturated, one might need the energy reach of a very high energy muon collider to probe these strong interactions.

Supersymmetry

If a Higgs boson is discovered at the LHC or earlier, then the nonperturbative mechanisms discussed in the two previous sections will fall (further) out of favor, and supersymmetric scenarios will dominate discussion. Naturalness arguments indicate that at least part of the supersymmetric spectrum should be probed by the LHC. It is possible that the LHC and linear colliders will uncover only part of the supersymmetric (SUSY) spectrum. In fact the lightest two generations of squarks and sleptons might appear at the multi-TeV scale without violating the naturalness arguments. The absence of certain supersymmetric partners being produced below the TeV energy scale would certainly compel us to go to higher energies. One should also bear in mind that the arguments based on naturalness are not as ironclad as those based on unitarity and might be evaded for reasons that will become clear only after we discover the supersymmetric spectrum. In any case, detailed studies of the supersymmetric spectrum will shed light on the mechanism of supersymmetry breaking and focus the attention of theorists on those models which are in agreement with the experimental data.

A more ambitious goal would be to try to observe the physics of a supersymmetry breaking sector directly. There are various scenarios for the breaking of supersymmetry, and if one is seriously considering multi-TeV muon colliders, then there is a possibility that this new physics might be probed directly. In gravitationally mediated SUSY breaking, the dynamical sector is hidden and couples only via gravitational couplings to the supersymmetric Standard Model particles. However other scenarios of SUSY breaking are possible, and these can be directly probed with sufficiently energetic collisions. In gauge mediated SUSY breaking scenarios, for example, there is just such another sector (known as the messenger sector) which occurs at a scale beyond that which can be probed at the LHC. This messenger sector might be accessible at a very high energy muon collider. The LHC has

the potential to indirectly provide clues about the source of SUSY breaking by measuring the spectrum of superpartners and perhaps seeing radiative decays in the case of gauge mediated SUSY breaking. In fact by measuring the location of displaced vertices (relative to the interaction point) from the radiative decay of the next-lightest supersymmetric particle one can put a constraint on the scale of the gauge mediation sector as first suggested in a Very Large Hadron Collider study⁶.

Gauge Bosons

A favorite target for new physics is the possibility of new gauge bosons beyond those found in the Standard Model. Many models predict new gauge bosons, and the observations at the LHC and future linear colliders might provide the motivation for going to even higher energies to find the new heavy gauge bosons directly. One might first reveal the existence of these particles via radiative return^{7,8} whereby a vector boson with mass less than the center-of-mass energy is produced in association with an energetic photon. Alternatively one could pinpoint the mass of the vector boson by doing precision measurements of the couplings and asymmetries at energies below the vector boson mass. In either case, one would ultimately want to build a collider with an energy equal to the mass of the vector boson and take advantage of the large cross section at the resonance energy.

Extra Dimensions

It was argued for a long time that the physics of extra dimensions was located near the Planck scale of 10^{19} GeV, and so possible evidence of these extra dimensions would be hard to come by in collider experiments. This argument is a dimensional one and depends on the conservative assumption that we live in four large spacetime dimensions, and the extra dimensions are compactified on a scale of the same order as the Planck scale itself. However in recent years, a “bring the mountain to Mohammed” strategy has emerged whereby the effects of these extra dimensions are located at a new scale at which they could “solve” the hierarchy problem. If this scenario proves true, then the effects of these extra dimensions might be probed at the LHC or at multi-TeV lepton colliders.

Conclusions

It is impossible to map out the direction of particle physics in the post-LHC era. However, if the past history of particle physics has taught us anything it is that the most important progress has occurred by going to higher and higher energies. It will be interesting in the coming years to learn whether muon colliders, and especially multi-TeV muon colliders, are realistic and economical.

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